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Characteristics and Chloride Permeability of Internally Cured Concrete

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This paper presents an experimental study on the physical characteristics of internally cured concrete using organic and inorganic materials, including chloride-related responses. The curing agents saturated before mixing the concrete are microporous lightweight aggregate (LWA), crushed returned concrete aggregate (CCA), and superabsorbent polymer (SAP). The inorganic agents (LWA and CCA) replace the concrete's fine aggregate by 25 to 75% in mass, while the organic agent (SAP) is added to the concrete mixture by 0.2 to 0.6% of the cement mass. A variety of test schemes are employed—namely, compression strength, resonant frequency, drying shrinkage, chloride permeability, and digital microscopy. Selected specimens are preloaded to examine the performance of the internally cured concrete subjected to service loading. The compressive strength of the concrete decreases as the amount of the curing agents increases. The strength decrease rate of the LWA- and SAP-mixed concrete is more rapid than that of the CCA-mixed concrete. In terms of resonant frequency, the LWA-mixed concrete is more susceptible relative to its CCA and SAP counterparts because of the LWA's microporous structure. The concrete mixed with LWA reveals dynamic to static elastic modulus ratios higher than the concrete with the other agents. Although all concrete mixtures' drying shrinkage is influenced by the agents' quantity, the inclusion of SAP results in more shrinkage. Electric charges passed through the internally cured concrete are higher than those of the control concrete, which represent the degree of chloride permeability. The occurrence of cracks in the concrete caused by preloading accelerates the mobility of chloride ions; nonetheless, the addition of SAP alleviates the implications of the mechanical damage.

Keywords: chloride; internal curing; material characterization; performance.

INTRODUCTION

Since the concept of high performance concrete (HPC) was developed in the early 1960s, the structural engineering community has been employing it for a number of applications, such as high-rise buildings and highway bridges. HPC provides enhanced strength, durability, and workability relative to ordinary concrete.[1] The water-cement ratio (*w*/*c*) of HPC is generally low; consequently, its hydration process may be restricted and some unfavorable behavior can be entailed (for example, shrinkage, warping, and early-age cracking of the concrete). Among many approaches that have been proposed to address these concerns, internal curing is recognized to be promising. This method is implemented by partially replacing conventional aggregates with pre-saturated constituents, which offer additional water to facilitate the hydration of cement and to control self-desiccation when the concrete is in a curing process.[2] Bentz et al.[3] studied the release of water inside concrete mixed with internal curing agents. The degree of hydration was reported up to 7 days, associated with three-dimensional (3-D) microtomography for moisture detection. The water-filled pores of the pre-saturated agents became empty after 1 day of hydration. Craeye et al.[4] reviewed previous research on polymer-based materials as internal curing agents for bridge deck application. The amount of materials added to concrete mixtures was typically 0.3 to 0.6% of cement mass. The autogenous shrinkage and crack resistance of the concrete were enhanced; however, its mechanical properties (strength and elastic modulus) were sacrificed. Gesoglu et al.[5] tested concrete mixed with an internal curing agent called ground-granulated blast-furnace slag. Drying shrinkage and cracking of the concrete were examined using prisms and hollow cylinders, respectively. The development of shrinkage strain and crack width was controlled by the porosity and water absorption of the agent. Kim and Lee[6] evaluated the potential of untreated coal bottom ash as an internal curing agent alongside absorption and desorption characteristics. Owing to the agent, the autogenous shrinkage of internally cured concrete was reduced.

Several regions in the United States rely on the use of excessive deicing agents in winter for the safety of motorists driving on highway bridges. Because concrete is a porous material and deicing agents are detrimental to the longevity of reinforced concrete decks, the penetration mechanism of chlorides and corresponding consequences are of interest. As in the case of ordinary concrete members, HPC-based bridge members are subjected to corrosion induced by chloride penetration, and their performance may be degraded from both serviceability and strength perspectives. Current knowledge on the material-level behavior of HPC with internal curing agents is limited when exposed to aggressive chloride environments.

Notwithstanding the recent advances in internally cured concrete, a comparative study on the performance of various curing agents, particularly for organic and inorganic materials, needs more effort to understand their physical characteristics and chloride-related responses. This paper reports an experimental program examining the characteristics of concrete mixed with three types of curing agents, including a technical aspect dealing with chloride permeability that is important from a performance point of view.

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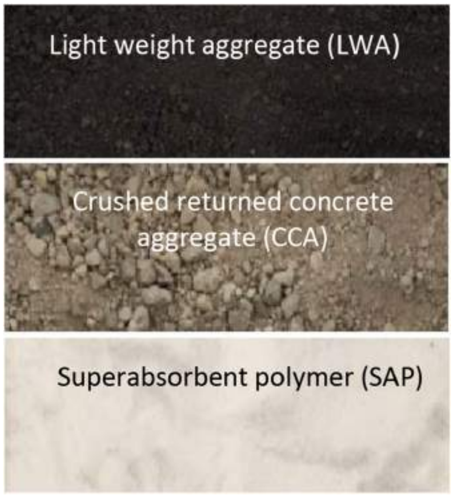


Fig. 1—Internal curing agents.

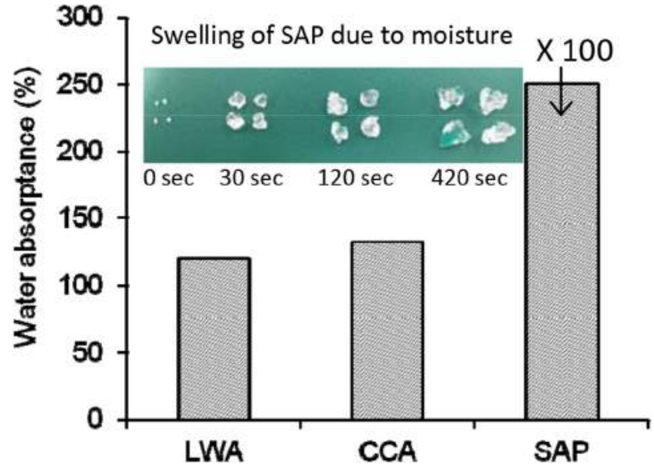


Fig. 2—Average water absorptance.

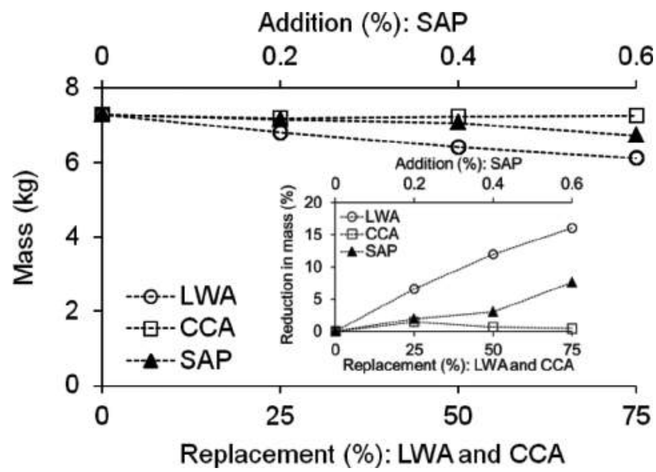


Fig. 3—Change in mass of concrete prisms.

RESEARCH SIGNIFICANCE

Despite practical significance, there is a dearth of research on the performance of HPC internally cured using organic and inorganic agents subjected to chloride ingress. The research discusses material characterization and chloride-related matters, depending upon the amount of the curing agents, with the presence of mechanical distress representing a service condition on site. The interaction between the curing agents and other constituents is crucial to understand the physical behavior and deterioration mechanisms of the internally cured concrete.

EXPERIMENTAL PROGRAM

Materials

The default constituents of concrete were portland cement (446 kg/m^3 [27.8 lb/ft^3]), coarse and fine aggregates (1095 and 600 kg/m^3 [68.4 and 37.5 lb/ft^3], respectively), and water (205 kg/m^3 [12.8 lb/ft^3]). Internal curing agents mixed with the concrete were lightweight aggregate (LWA), crushed returned concrete aggregate (CCA), and superabsorbent polymer (SAP), as shown in Fig. 1. The LWA agent (density = 800 kg/m^3 [50 lb/ft^3]) is a shale-based microporous material with a fineness modulus of 3.72 and a specific gravity of 1.51.[7] The CCA agent (density = 2390 kg/m^3 [149 lb/ft^3]) shows environmentally friendliness owing to the use of recycled products with a fineness modulus of 2.71.[8] The granular solid SAP agent (density = 659 kg/m^3 [41 lb/ft^3]) has a cross-linked sodium polyacrylate structure and is insoluble to water.[9]

Specimens

Specimens were prepared to examine the compressive strength (cylinders: 100 mm [4 in.] in diameter by 200 mm [8 in.] in length), resonant frequency (prisms: 75 mm [3 in.] in depth by 100 mm [4 in.] in width by 400 mm [16 in.] in length), and drying shrinkage (prisms: 100 mm [4 in.] in depth by 100 mm [4 in.] in width by 280 mm [11 in.] in length) of the internally cured concrete. Test variables encompassed the type and amount of the curing agents. For the inorganic agents (LWA and CCA), the quantity of the fine aggregate was replaced by 0 to 75% in mass at an interval of 25%. On the other hand, the organic agent (SAP) was added to the concrete mixture by 0 to 0.6% of the cement mass at an interval of 0.2%. The LWA and CCA agents were immersed in water for 24 hours before mixing concrete, whereas the SAP agent required approximately 10 minutes to fully absorb water. Figure 2 exhibits the average water absorptance of these curing agents. The saturated LWA agent revealed a swelling of 120% compared with the dry state, which is 9.6% less than the CCA agent's swelling. The amount of water absorptance in SAP was considerably larger than the absorptance of the other agents (Fig. 2, inset), which is typical in such a synthetic material.[4] After curing the concrete prisms (75 mm [3 in.] in depth by 100 mm [4 in.] in width by 400 mm [16 in.] in length) for 28 days, their mass was measured, as shown in Fig. 3. The mass of the concrete with LWA gradually decreased from 7.3 kg (16.1 lb) to 6.7 kg (14.8 lb) at 0% and 75% replacement ratios, respectively, whose variation was more than those of the CCA- and SAP-mixed concrete specimens. This can be explained by the fact that the density of LWA was 33.5% of that of CCA, and the amount of SAP added to the concrete was relatively insignificant.

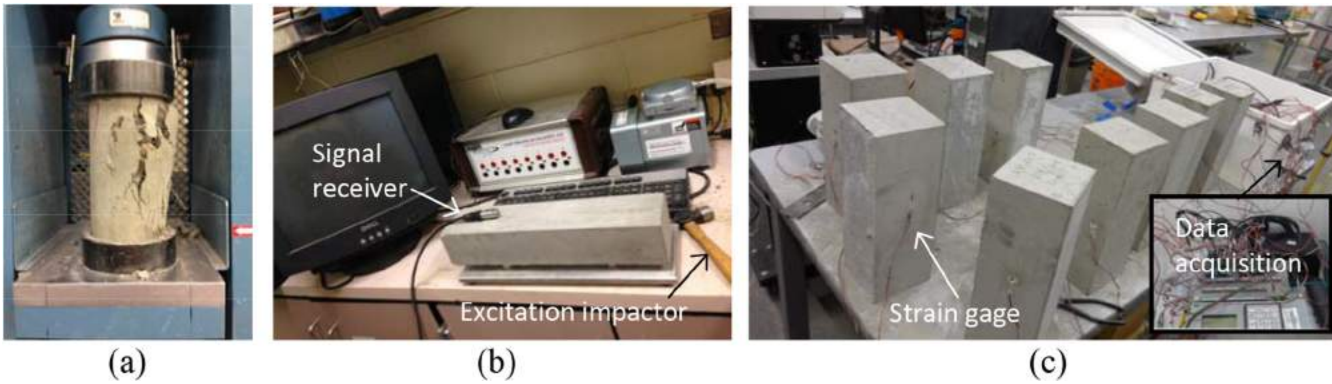


Fig. 4—Material characterization: (a) compressive strength; (b) resonant frequency; and (c) drying shrinkage.

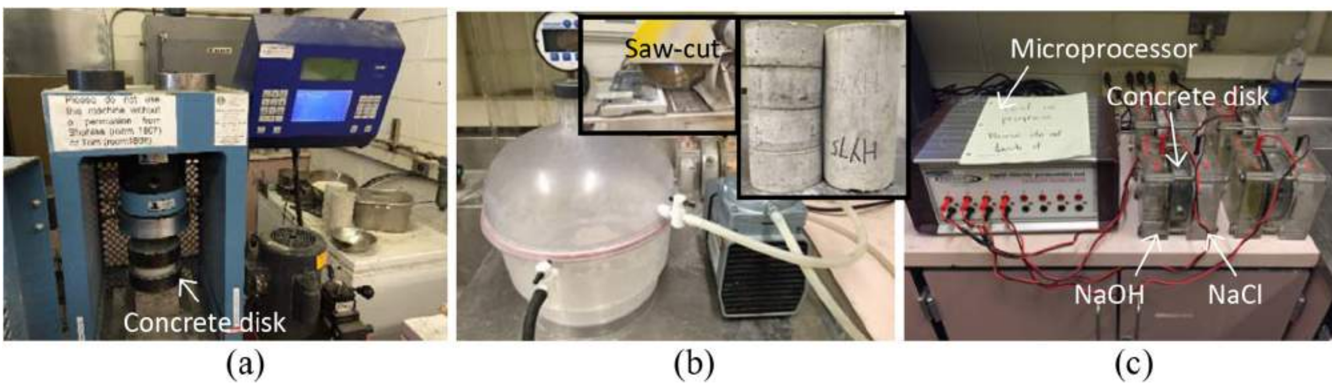


Fig. 5—Chloride penetration: (a) preloading; (b) vacuum chamber; and (c) test cells.

Test schemes

Compressive strength—The prepared concrete cylinders were wrapped with plastic sheets to preclude moisture ingress from outside and were cured at room temperature for 28 days. A total of 30 cylinders were then monotonically loaded to failure (three specimens per category in compliance with ASTM C39[10] at a rate of 0.25 ± 0.05 MPa/s [35 ± 7 psi/s], as shown in Fig. 4(a)).

Resonant frequency—Following ASTM C215,[11] an impact resonant test was conducted. After measuring mass after 28 days of casting, each test specimen cured with plastic sheets was placed on two steel rods spaced at a distance of 180 mm (7 in.), followed by positioning a signal receiver (Fig. 4(b)). The prism was excited by an impactor near its end to detect fundamental frequencies that were recorded by a computerized data acquisition system. To ensure test results, the frequencies were repeatedly measured three times per specimen, and the readings were averaged. In accordance with Eq. (1), the specimen's dynamic elastic modulus, E_D, was calculated[11]

$$E_D = 0.9464\left(\frac{L^3T}{bt^3}\right)Mf^2 \quad (1)$$

where L, b, and t are the length, width, and thickness of the prism, respectively; T is a correction factor determined by the ratio of the radius of gyration to the length of the specimen (T = 1.23 in the present test); and M and f are the mass and fundamental frequency of the specimen, respectively.

Drying shrinkage—The prisms were stripped after 24 hours of casting, as recommended by ASTM C157.[12] Immediately after demolding, strain gauges were bonded at mid-height of the specimens to monitor drying shrinkage for 30 days (Fig. 4(c)). The data acquisition system was programmed to record strain data every 10 minutes. During shrinkage testing, the temperature and humidity of the laboratory were 20°C and 52%, respectively, on average.

Chloride permeability—ASTM C1202[13] was referenced to investigate the influence of internal curing agents on chloride-permeability characteristics in the concrete. The prepared cylinders (100 mm [4 in.] in diameter) were cut to a length of 50 mm (2 in.) using a diamond saw after 28 days of casting. To represent mechanical damage that may happen on site, two types of disks were tested with and without preload. The preload level applied was 50% of the concrete strength without any curing agents (f_c' = 40 MPa [5800 psi], on average), as shown in Fig. 5(a). The concrete disks were then saturated in a vacuum chamber for 1 hour (Fig. 5(b)), followed by an 18-hour immersion period. Each disk was positioned between two test cells filled with a 3% concentration of sodium chloride and a 0.3M sodium hydroxide, and clamped with bolts and nuts (Fig. 5(c)). To prevent leaking of the solutions, rubber sealers (o-rings) were layered on both sides of the disk. Electricity was supplied at a 60 V potential for 3 hours through cables connecting a microprocessor unit and the two cells. These procedures were repeated with five specimens per test category and their responses to chlorides were measured every 30 minutes.

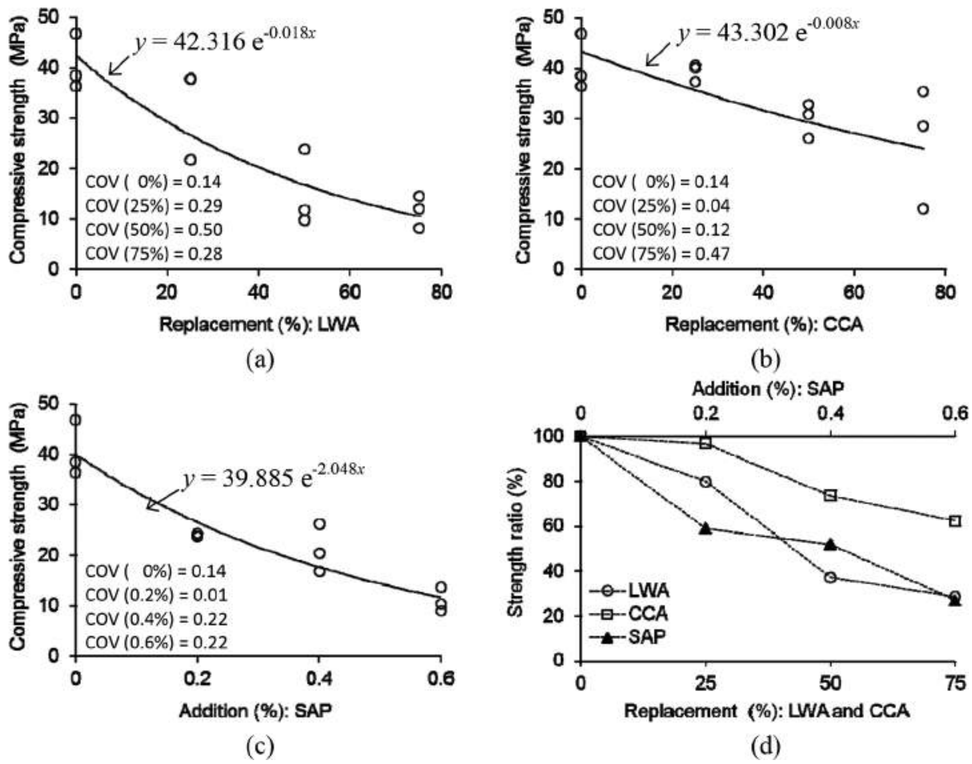


Fig. 6—Compressive strength of concrete with internal curing agents: (a) LWA; (b) CCA; (c) SAP; and (d) strength ratio on average.

Digital microscope—An optical high-resolution microscope (1280 x 1024 pixels at a rate of 30 frames/s) was used to examine the possible occurrence of cracks on the aforementioned concrete disks by drying shrinkage and mechanical loading. The microscope is equipped with an adjustable polarizer to remove reflections, thereby enhancing the contrast of an object.

RESULTS AND DISCUSSION

Compressive strength

Figure 6 shows the variation of compressive strength with the amount of curing agents in the concrete. For the specimens mixed with LWA (Fig. 6(a)), a rapid strength reduction was observed with a replacement ratio, including an exponentially decreasing fitted curve. The degree of scatter was noticeable, as evidenced by the coefficients of variation (COV) spanning from 0.28 to 0.50, which are larger than that of the control concrete (COV = 0.14). This fact illustrates that: 1) the LWA agents were erratically dispersed inside the concrete; and 2) the inclusion of the agents created pseudo-voids in the cement paste, so that the increased replacement ratio weakened the load-bearing structure of the cylinder. The strength of the CCA-mixed concrete was also reduced as the quantity of the curing agent rose (Fig. 6(b)), whereas the decrease rate represented by the slope of the fitted curve was not as significant as the rate of the LWA-mixed concrete. The trend of strength variation in the SAP-mixed specimens was similar to that of the LWA case with lower COVs, as shown in Fig. 6(c). For comparison, the average strength decrease ratios of each concrete mixture are plotted in Fig. 6(d). A 3.1% reduction in strength was noticed for the CCA-mixed concrete at a replacement ratio of 25%, which is significantly lower than the 71.3% decrease of its LWA counterpart. With an increase in the replacement ratio, the CCA-concrete's strength was drastically diminished to 26.3% and 37.6% at replacement ratios of 50% and 75%, respectively. These reduction ratios were still higher than those of the LWA specimens, however. This observation is ascribed to the fact that LWA has larger pores than CCA[8]; accordingly, the microstructure of the LWA-concrete collapsed faster than that of the CCA-concrete at identical replacement ratios. The SAP-mixed specimen exhibited a rapid decrease of 40.9% in strength at a 0.2% addition ratio, followed by decreases of 47.9% and 72.9% at 0.4% and 0.6% ratios, respectively. These facts indicate that although the internal curing agents can facilitate the hydration process of the concrete, their use should be properly determined to preserve a required concrete strength (it should be noted that this experimental program intentionally employed a large amount of curing agents to examine their effects).

Resonant frequency and dynamic modulus

The resonant frequency of the internally cured concrete is shown in Fig. 7(a). As the quantity of curing agents increased, the frequency of all prisms diminished because the degree of saturation affected frequency development, which is related to the capillary pores and moisture content of the concrete.[14] Detailed responses were dependent upon agent types, however. The concrete mixed with LWA exhibited a gradual reduction in frequency with the replacement ratio. By contrast, the prisms involving CCA and SAP revealed remarkable drops at 25% replacement and 0.2 addition ratios, followed by plateau-like responses. Overall, the frequency of the LWA-mixed concrete was less susceptible

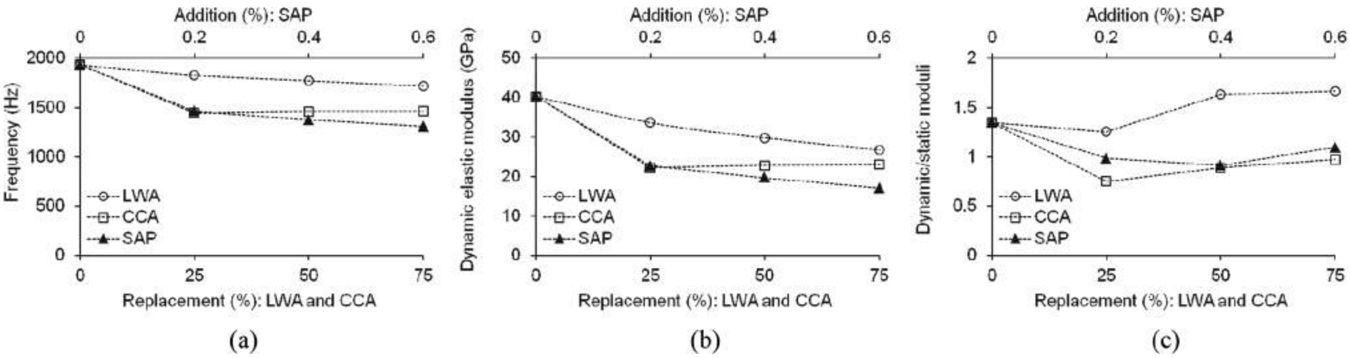


Fig. 7—Fundamental resonant frequency test: (a) average impact resonant frequency; (b) average dynamic elastic modulus; and (c) ratio between dynamic and static moduli.

to the inclusion of curing agents in comparison with those of other mixtures. These observations are attributed to the fact that the average mass of the LWA prisms was less than the mass of the others (Fig. 3); hence, the frequency of the former was relatively higher (frequency f is proportional to the stiffness of a material k and is inversely proportional to its mass m: $f \propto k / m$). Furthermore, the inclusion of the curing agents weakens the concrete's stiffness because the strength of the saturated agents is lower than that of conventional aggregates[5]; as such, the frequencies had a propensity to dwindle with the increased amount of the curing agents (Fig. 7(a)). The stabilized frequencies of the specimens mixed with CCA and SAP beyond 25% replacement and 0.2% and addition ratios illustrate that the stiffness and mass of the concrete varied in a similar rate. Figure 7(b) reveals the average dynamic elastic modulus of the concrete. Because the vibration-based elastic moduli were calculated based on the fundamental frequencies (Eq. (1)), the trend of variation in these two properties was identical. The viscoelastic and microplastic behavior of the saturated concrete lowered the dynamic moduli.[15] The dynamic moduli of the concrete were compared with the static moduli estimated by $E_S = 57{,}000\sqrt{f_c'}$ in psi and $= 4700\sqrt{f_c'}$ in MPa,[16] as shown in Fig. 7(c). At the control state of 0%, the ratio of the dynamic and static moduli was 1.35. As the amount of the curing agents increased, the heterogeneity and anisotropy of the concrete were augmented because the agents are not typical concrete components and randomly distributed in the mixtures. As a result, the ratio of the LWA-mixed concrete rose up to 1.67, while those of the CCA- and SAP-mixed concrete decreased to 0.94 on average. This can be explained by the fact that the microporous LWA agent accompanied higher resonant frequencies than the CCA and SAP agents, as explained earlier. It is therefore stated that the type of a curing agent is of great importance when determining the dynamic elastic modulus of the concrete.

Shrinkage

Figure 8 exhibits the drying shrinkage of the unrestrained concrete prisms. Given that the autogenous shrinkage and drying shrinkage of concrete take place simultaneously, these shrinkage types may not need to be distinguished in practice.[17] The control specimen without curing agents (0%) revealed a linearly decaying response up to 20 days (the loss of adsorbed water from calcium silicate hydrate), beyond which a stepwise strain development was noticed (Fig. 8(a)). This behavior illustrates that the concrete's dimensional stability, primarily the deformation of the fully or partially hydrated cement paste, was changed by shrinkage. It is worth noting that although drying shrinkage was not measured inside the concrete prism, nonuniform strain gradients are anticipated because the progression of drying on the surface and the inside of the concrete is not identical.[18] For the LWA-based specimens, the time-shrinkage behavior was markedly influenced by the amount of the curing agent, as shown in Fig. 8(a). The shrinkage strain of LWA-25% (25% replacement) was almost linear down to -504×10^{-6} at 30 days; however, the strain of LWA-50% (50% replacement) rapidly decreased to -394×10^{-6} at 5 days, followed by a constant reduction slope similar to that of the LWA-25% specimen. When the replacement ratio increased to 75% (LWA-75%), the initial strain-decrease became more pronounced (-852×10^{-6} at 5 days) and the response stabilized with time. It is presumed that the water-release rate of LWA was controlled by replacement ratios; specifically, the 25% replacement case showed a steady release rate, whereas the 50 and 75% cases swiftly released water at the nascent curing stage and the ensuing rates decelerated. Microscale examinations on the water-release characteristics of LWA should be a follow-up research subject to clarify the relationship between the replacement ratio and water-release rates. Shown in Fig. 8(b) are the shrinkage responses of the prisms mixed with CCA. As is the case for the LWA-mixed specimens, the degree of drying shrinkage was a function of the CCA amount. The strain development of the CCA-mixed concrete was, however, much lower than that of its LWA counterpart. For instance, CCA-75% revealed 45.8% and 27.5% lower strains at 15 and 30 days in comparison with LWA-75%, respectively. In addition, the early-age strains of CCA-50% and –75% at 5 days were 56.3% and 46.0% of the strains of LWA-50% and –75%, respectively. In summary, the water release capability of LWA is superior to the capability of CCA. The specimen with a 0.2% SAP addition (Fig. 8(c)) demonstrated more strains than those with the 25% replacement of LWA and CCA up to 15 days; thereafter, the former's strain became plateaued. With an increase in the SAP addition ratio to 0.4 and 0.6%, the extent of drying shrinkage was significant. For example, -822×10^{-6} and -1233×10^{-6} for the 0.4% and 0.6% cases were, respectively, measured at 20 days.

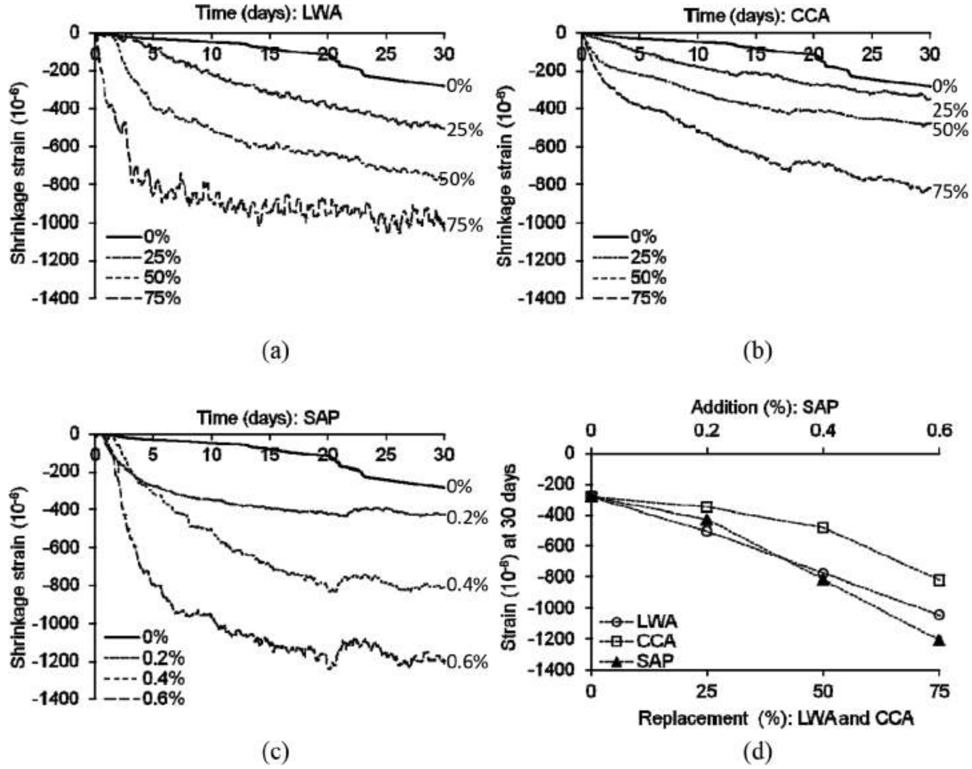
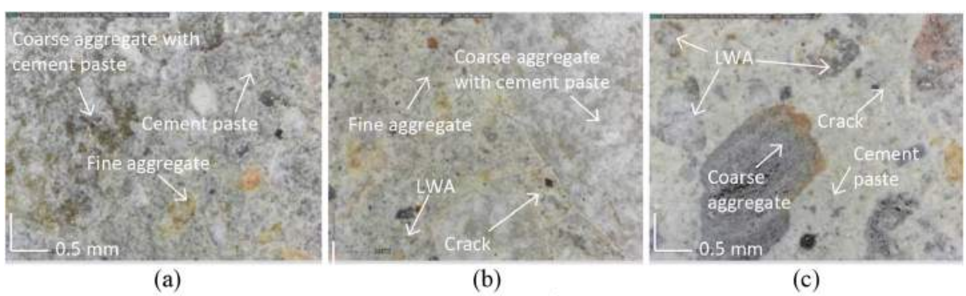


Fig. 8—Drying shrinkage of 30 days: (a) LWA; (b) CCA; (c) SAP; and (d) comparison of strains at 30 days. (Note: 1 mm = 0.0394 in.)



[1 mm = 0.0394 in.]

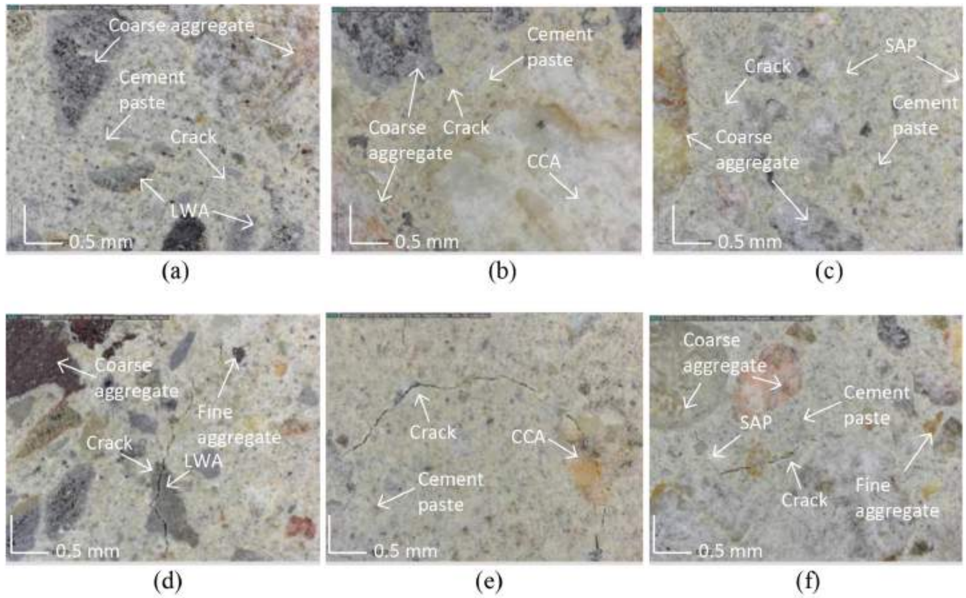
Fig. 9—Effect of LWA inclusion on microcrack development without preload (100× magnification): (a) 0% replacement; (b) 25% replacement; and (c) 50% replacement.

Microscopic image

Figure 9 shows the microscopic images of the LWA-mixed concrete disks at 28 days without preload (other disks with CCA and SAP exhibited similar images that are not given for brevity). At a replacement ratio of 0%, no visual cracks were noticed at the 100× magnification scale employed (Fig. 9(a)). When the curing agents were included, however, very fine cracks were observed in the hydrated cement paste (Fig. 9(b) and (c)). The occurrence of such cracks, albeit insignificant, is attributable to the deformation of the cement paste alongside the volumetric changes of the curing agents caused by releasing the absorbed water. The preceding images indicate that microcracks existed prior to the use of the internally cured concrete. It should be noted that concrete cracks less than 0.1 mm (0.0039 in.) may not be readily detectable by the naked eye and may not be problematic in ordinary practice.[19] Although microcracks are common in concrete mixtures,[20] the microcracks in the cement paste are a contributor that has decreased the compressive strength of the internally cured concrete (Fig. 6). The effects of preload on crack development of the internally cured concrete disks are shown in Fig. 10 (owing to page restrictions, only the 75% replacement of LWA and CCA and the 0.6% addition of SAP are presented). As stated previously, the inclusion of the curing agents caused insignificant microcracks and the agent types did not affect the formation of autogenous cracks (Fig. 10(a) to (c)). In contrast, the degree of cracking was remarkable with the presence of preload (Fig. 10(d) to (f)), including an apparent crack across the LWA curing agent (Fig. 10(d)). The implications of preload-induced cracks will further be elaborated in the subsequent section.

Chloride permeability

Electric charge—The average charges passed across the concrete disks are summarized in Fig. 11(a) to (c), which



[1 mm = 0.0394 in.]

Fig. 10—Effect of preload on microcrack development (100× magnification): (a) 75% LWA without preload; (b) 75% CCA without preload; (c) 0.6% SAP without preload; (d) 75% LWA with preload; (e) 75% CCA with preload; and (f) 0.6% SAP with preload.

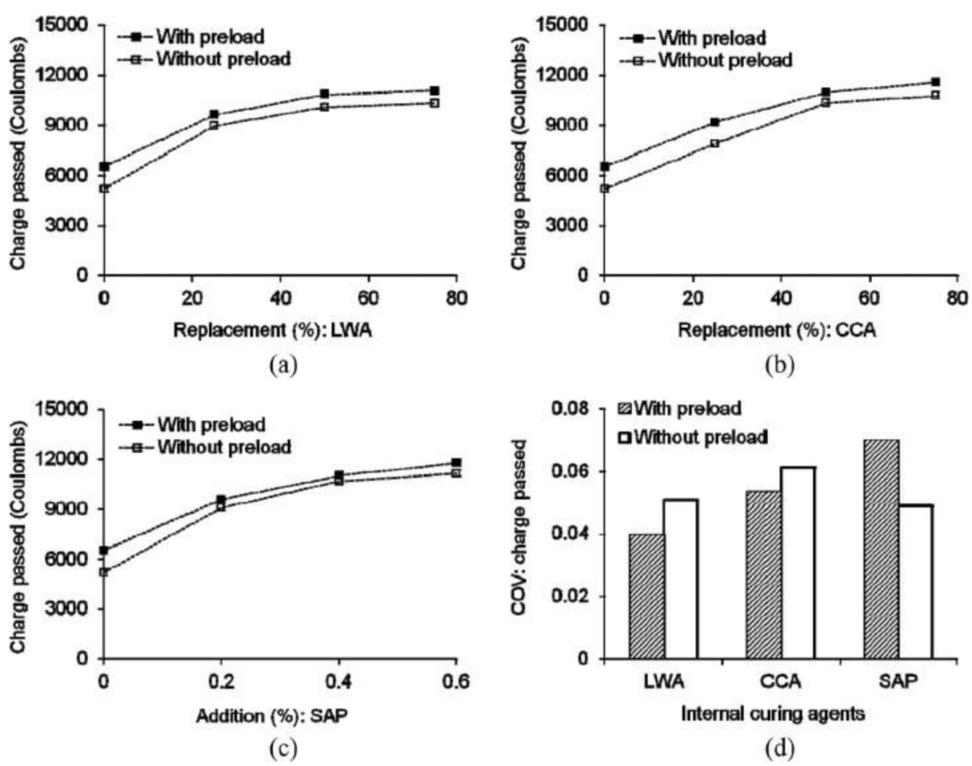


Fig. 11—Chloride permeability with average charge passed: (a) LWA; (b) CCA; (c) SAP: and (d) degree of scatter. (Note: 1 g = 0.002 lb.)

represent the degree of chloride permeability. The charges of the LWA-mixed concrete increased in a parabolic shape until the 50% replacement ratio was reached and the charges stabilized, as shown in Fig. 11(a). This observation means that the concrete micropores were saturated by the sodium chloride solution; accordingly, the flow of chloride ions became constant after the 50% replacement ratio. The presence of preload augmented the extent of charges by 6.7% on average, which points out that the preload-induced cracks allowed more chlorides across the concrete. The difference between the cases with and without preload at the 0% replacement ratio was higher than the difference at other ratios. The reason is that the presaturated LWA agents accelerated the mobility of chloride ions; thus, the effect of preload was relatively insensitive. Even though the charge values were high in accordance with ASTM C1202 (chlo-

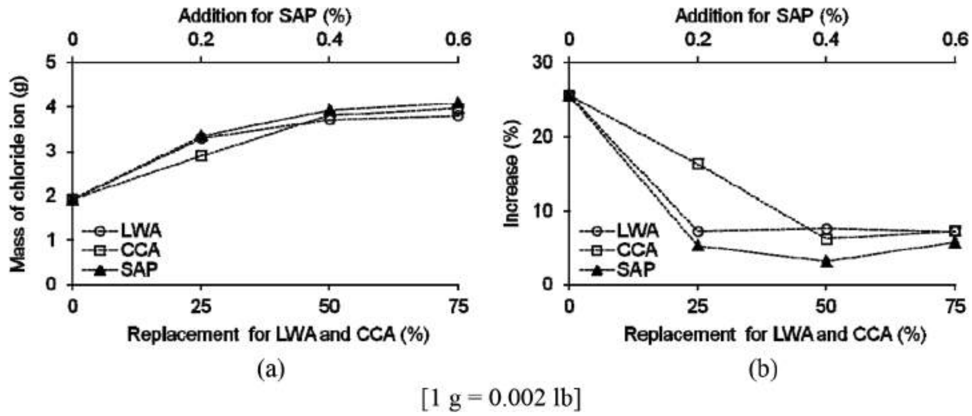


Fig. 12—Mass of chloride ions in concrete disks: (a) without preload; and (b) increase in chloride-ion mass after preload.

ride permeability is high if a charge passed is more than 4000 Coulombs), these values are expected to decrease with time as reported by Joshi and Chan[21]; charges as high as 8000 Coulombs within 28 days decreased below 1000 Coulombs at 180 days. For the concrete with CCA, the development of charges was almost linear up to a replacement ratio of 50% and then its rate was diminished (Fig. 11(b)). The difference in charge between the CCA disks with and without preload was preserved until a 25% replacement, and the gap of these test categories was reduced at 50 and 75% replacement ratios. In terms of SAP-mixed concrete, the preload effect was not as significant as that of the concrete with the aforementioned inorganic curing agents (Fig. 11(c)) because the water absorptance of SAP was incomparably more (Fig. 2). The concrete with SAP is therefore less susceptible to mechanical distress from chloride permeability standpoints. Figure 11(d) compares the degree of scatter associated with chloride permeability for the internally cured concrete. The coefficients of variation (COV) of the concrete disks with LWA and CCA decreased by 21.6% and 13.1% due to the preload, respectively; however, the COV of the disks with SAP increased by 30.0%. It is speculated that the relatively large volume change of SAP after releasing water in tandem with the collapse of the microstructure due to the preload created randomly distributed micro-voids inside the concrete, which increased the level of uncertainty in measuring the permeability.

Estimation of chloride content—An analytical procedure was exploited to estimate the mass of chloride ions in the concrete disks, based on the following steps:

1. The average charges measured in the preceding chloride permeability test were gathered.

2. The number of chloride ions (Cl^-) passing through the concrete was calculated by the fact that each chloride ion brings a negative charge of -1.602×10^{-19} Coulombs.

3. The mole of chloride ions was determined using the number of chloride ions divided by Avogadro's number (6.02×10^{23}).

4. The mass of chloride ions in each test category was acquired with the molar mass of a chloride ion being 35.5 g (0.078 lb). The mass of electrons was negligibly small compared with that of the chloride ions.

The estimated mass of chlorides in the 0% control specimens without preload was 1.9 g (0.004 lb), on average, as shown in Fig. 12(a). The mass of chlorides increased noticeably when the internal curing agents were included in the concrete mixtures. The concrete with LWA revealed an increase in chloride mass of 3.3 g (0.007 lb), 3.7 g (0.0082 lb), and 3.8 g (0.0084 lb) at 25%, 50%, and 75% replacement ratios (that is, 74%, 95%, and 100% increases relative to the control), respectively. Similar increases in chloride mass were observed for the concrete mixtures with CCA and SAP. With the presence of preload, the mass of chlorides rose (Fig. 12(b)). The inclusion of the curing agents, however, alleviated the extent of chloride accumulation inside the concrete associated with the preload. It is hypothesized that the hydration of the concrete accelerated by the curing agents improved the bond between the cement and water molecules (that is, consolidated concrete), so that the detrimental distress generated by the preload was partially offset.

SUMMARY AND CONCLUSIONS

This paper has comparatively examined the physical characteristics of concrete mixed with organic and inorganic internal curing agents (microporous lightweight aggregate [LWA], crushed returned concrete aggregate [CCA], and superabsorbent polymer [SAP]), and evaluated chloride-related matters. The LWA and CCA agents replaced the concrete's fine aggregate by 25 to 75%, while the SAP agent is added by 0.2 to 0.6% of cement mass. A total of 30 cylinders, 60 prisms, and 100 disks were used for various tests: compression strength, resonant frequency, drying shrinkage, chloride permeability, and digital microscopy. To study the effects of mechanical damage that could happen during a service period, a preload of 50% of the control concrete strength was applied to selected specimens. Additional research is recommended to better understand the various aspects of internally cured concrete with a focus on time-dependent moisture release mechanisms through micropores, durability performance, and structure-level applications. The following conclusions are drawn:

- With an increase in the replacement ratio, the strength decrease rate of the LWA-mixed concrete was more rapid than CCA-mixed concrete. According to the measured coefficients of variation, the LWA and CCA agents were speculated to be dispersed erratically inside the concrete. The SAP-mixed concrete showed a strength decrease rate similar to the LWA case with lower coefficients of variation.

- The resonant frequency of the internally cured concrete decreased when the amount of the agents increased. The LWA-mixed concrete's frequency variation was not as sensitive to the agents' quantity as its CCA and SAP counterparts, primarily due to the microporous LWA's lighter mass. The ratio between the dynamic and static elastic moduli of the LWA-mixed concrete was noticeably high (up to 1.67), whereas the ratio of the CCA- and SAP-mixed concrete was close to unity.
- The concrete's drying shrinkage was influenced by the amount of the curing agents. The strain development of the SAP-mixed concrete was more pronounced than that of the LWA- and CCA-mixed concrete. Insignificant microcracks were observed in the internally cured concrete. After preloading the concrete, wider cracks were noticed, owing to mechanical damage.
- The electric charge of the concrete mixed with the internal curing agents was greater than that of the control concrete. The charges rose until the concrete's micropores were saturated by sodium chloride. The aforementioned preload-induced cracks facilitated chloride flows across the concrete, thereby increasing the quantity of chloride ions. In terms of chloride permeability, the concrete with the organic SAP agent was less sensitive to mechanical damage relative to the concrete with the other inorganic agents.

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